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Summary

Measurements of the absorption of sound by functional absorbers (panels of porous material mounted so that both sides are exposed to the sound field) are described, the absorbers being arranged in a number of different configurations. The effect of increasing the surface density of the absorbing panels without significantly changing their thickness or porosity is examined, and deductions are made about the mechanisms of absorption at different frequencies.

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1. INTRODUCTION

The term "functional absorber" has come to mean the use of panels or sheets of porous material mounted so that both sides are exposed to the sound field: very often the panels are suspended from the ceiling of the treated enclosure. The technique is now often used for providing absorption in noisy areas (e.g. machine shops) where the relatively inexpensive method of constructing and fixing the absorber, and the use of an otherwise unoccupied space, are attractive. Intuitively it would be expected that such an absorber would be most effective for the higher audio frequencies: this is not necessarily a severe disadvantage in industrial noise control, where a reduction of the sound pressure level (spl) at such frequencies can bring, for example, increased speech intelligibility as well as a less unpleasant working environment. The use of such techniques for studio acoustic treatment offers the possibility of providing a relatively large total amount of sound absorption while minimising the area of wall surface occupied by the treatment: indeed, the surface to which the functional absorber is fixed can itself carry more acoustic treatment, particularly if the functional absorber is placed some distance from it (for example, suspended well below a ceiling which itself carries absorbers). If this approach is to be adopted, however, reasonably accurate assessments of the absorption characteristics of particular arrangements of functional absorbers are required. This Report presents the results obtained when one particular form of functional absorber construction was arranged in a number of different ways in a reverberation room of volume 106 m^3, and also discusses the effect of increasing the surface mass of the absorber, by constraining the absorbing material between welded steel grids, without significantly altering its porosity or thickness.

2. ABSORBER CONSTRUCTION AND EXPERIMENTAL ARRANGEMENTS

The basic absorbing element was a mineral wool blanket 1.2 m long, 0.6 m wide and 30 mm thick, supported round its periphery by a light wooden frame provided with hardboard side-cheeks (Fig. 1). Two cross-members were attached to one edge of the frame so that a panel could be supported with either the short edge (Fig. 2(a)) or the long edge (Fig. 2(b)) normal to a surface of the reverberation room: furthermore, panels could either be stood on the floor of the room or project from its walls. The mineral wool blankets could also be hung from the ceiling (Fig. 2(c)): in this case the frame was not used, the blankets being gripped between two lengths of hardboard along one side, to which the supports were also attached.

Sixteen absorbers were used in most of the tests. Many of the absorber arrangements were based on a "criss-cross" pattern (Fig. 3), the centre-lines of the absorbers normal to the surface on which they were mounted being arranged on a 1.2 m grid, irrespective of whether this was the short or long dimension. This arrangement gave an "absorber density" of one per 1.44 m^2 of surface covered, or in other words 0.7 absorber per square metre. In some cases all sixteen absorbers were placed on the floor of the reverberation room, or hung from the ceiling, while in other cases the absorbers were arranged in four groups, each of four panels, on three walls and the floor of the room. Tests were also carried out with the absorber arrangements conforming to these general patterns but with some of the panels omitted, as well as with different "in-line" arrangements of the panels.

Absorption coefficients were calculated in the

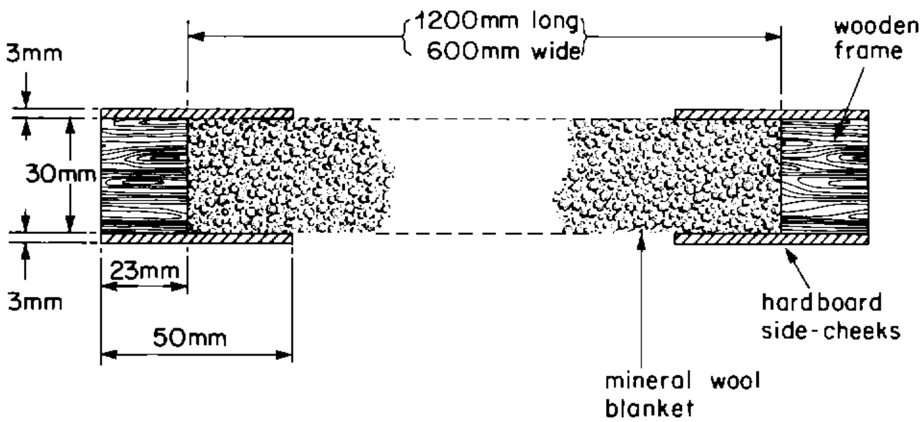

Fig. 1
Construction of functional absorber panel.

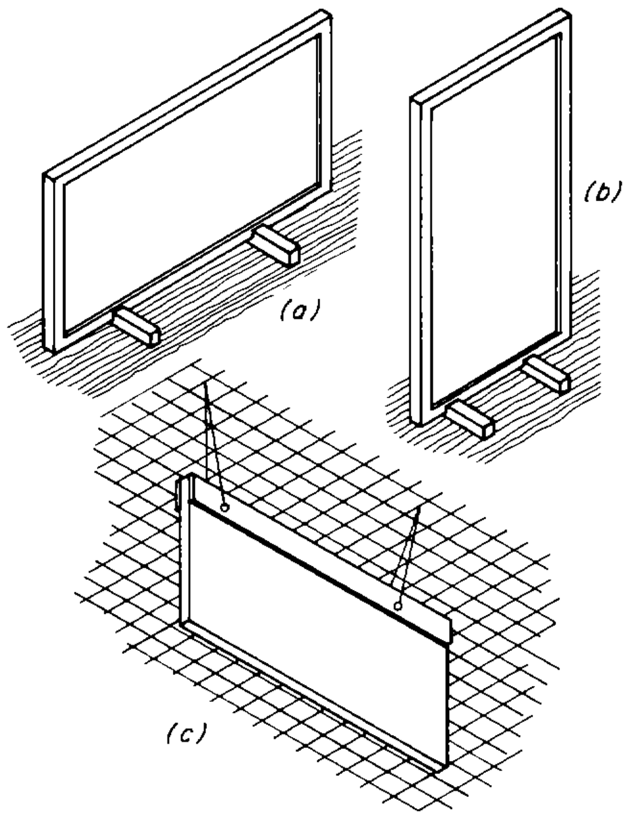

Fig. 2 - Arrangements for supporting panel.

(a) Short edge normal to surface.
(b) Long edge normal to surface.
(c) As for (a) but hung from the ceiling.

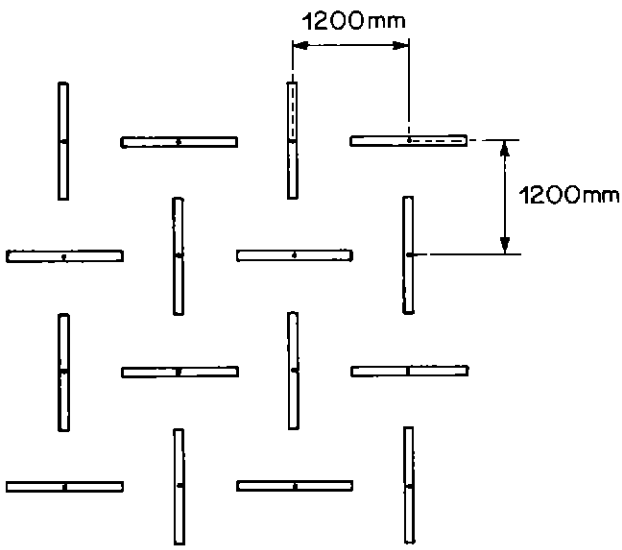

Fig. 3 - Basic "criss-cross" absorber arrangement.

conventional manner from measurements of reverberation time with the room first empty and then with the test absorbers in place. The calculation was based on the Eyring formula[1]

$$T = 0.163 \frac{V}{4mV - S\ln(1-\bar{\alpha})} \qquad (1)$$

where T is the reverberation time in seconds,
V is the volume of the room in m^3,
S is the total area of all the room surfaces in m^2,
$\bar{\alpha}$ is the mean absorption coefficient,
and m is the absorption constant of air in nepers m^{-1}

In Equation 1,

$$\bar{\alpha} = \frac{1}{S}(S_1\alpha_1 + S_2\alpha_2 + \ldots) \qquad (2)$$

where subscripts 1, 2, . . . refer to surface areas and absorption coefficients of different materials $(S_1+S_2+\ldots) = S$, and m is given by

$$\frac{p_t^2}{p_o^2} = \exp(-mct) = \exp(-ml) \qquad (3)$$

where, in turn, p_t and p_o are sound energy densities, at time zero and t respectively, when air absorption is the only acoustic loss mechanism present,

c is the velocity of sound,

and l is the path length travelled by the sound ($l = ct$).

It may be noted that all the values of absorption coefficient referred to in this Report have been obtained by using a value of test absorber area equal to the sum of the nominal areas (i.e. the area of *one* face) of each of the absorbing panels, irrespective of the way in which the absorbers were arranged for the tests.

The results of tests using the absorber construction described above (i.e. a mineral wool blanket supported by a light wooden frame) are described in Sections 3.1 - 3.4 inclusive of this Report. Although this form of construction was robust enough for test purposes it was not thought to be suitable for practical use, and for this reason some tests were carried out with the mineral wool blanket supported on each side by a sheet of welded steel grid having a mesh of 12 mm (½ inch). It was found that the presence of the steel grid increased (on average) the low and mid-frequency absorption. The results obtained with the steel grids in place are described in Section 3.5 and discussed in Section 4.1.

3. MEASURED ABSORBER PERFORMANCE

3.1. Tests with absorbers in "criss-cross" pattern, in four groups

Four groups, each containing four absorbers, were placed on three walls and the floor of the

reverberation room. Fig. 4(a) shows the arrangement when the short axes of the absorbers were normal to the room surfaces: the same absorber orientation and centering was used when the long absorber axes were normal, as discussed in Section 2. In this Figure, as well as others showing the arrangements of absorbers for different tests, an "opened-up box" representation of the reverberation-room surfaces has been used. The absorber arrangement is shown as it would appear to an observer in the room looking at the surface in question. For greater clarity, only those surfaces actually carrying absorbers are shown.

Measurements were also made with only two absorbers (Fig. 4b) and one absorber (Fig. 4c) present in each group. In general, the absorption was found to rise from a relatively low value (around 0.2) at low frequencies to around unity at 400 Hz, irrespective of the number of absorbers present in each group. Above 400 Hz, however, the absorber behaviour did depend on the number of absorbers present, a higher absorption coefficient value being obtained when less than the full number of absorbers were present. The absorption coefficient continued to rise up to a frequency of 1 kHz, and remained essentially constant for frequencies higher than this. No significant difference was found in absorber behaviour when the long or short axes were normal to the adjacent room surface.

For diagrammatic clarity, Fig. 5 shows only the average absorber behaviour under these conditions (solid lines) together with highest and lowest values obtained (dotted lines). The rise in absorption coefficient at frequencies higher than 2.5 kHz is thought to have been caused by incorrect compensation for changes of sound absorption during the tests caused by changes in the humidity of the air in the reverberation room (note the increasing spread of values) and should be discounted as shown by the horizontal dashed lines.

At low frequencies, the value of absorption coefficient obtained for particular one-third octave bands differed considerably from one absorber arrangement to another. In addition, results obtained using the same absorber arrangement showed considerable irregular changes of absorption coefficient between adjacent frequency bands.

In view of these effects, the residual irregularities in average absorber behaviour shown in Fig. 5 are not thought to be intrinsic to the absorber arrangement used in the tests. Rather, they are more likely to be caused by characteristics (room mode patterns) of the reverberation room. The "smoothed" characteristics shown in Fig. 6 have been obtained by ignoring these irregularities.

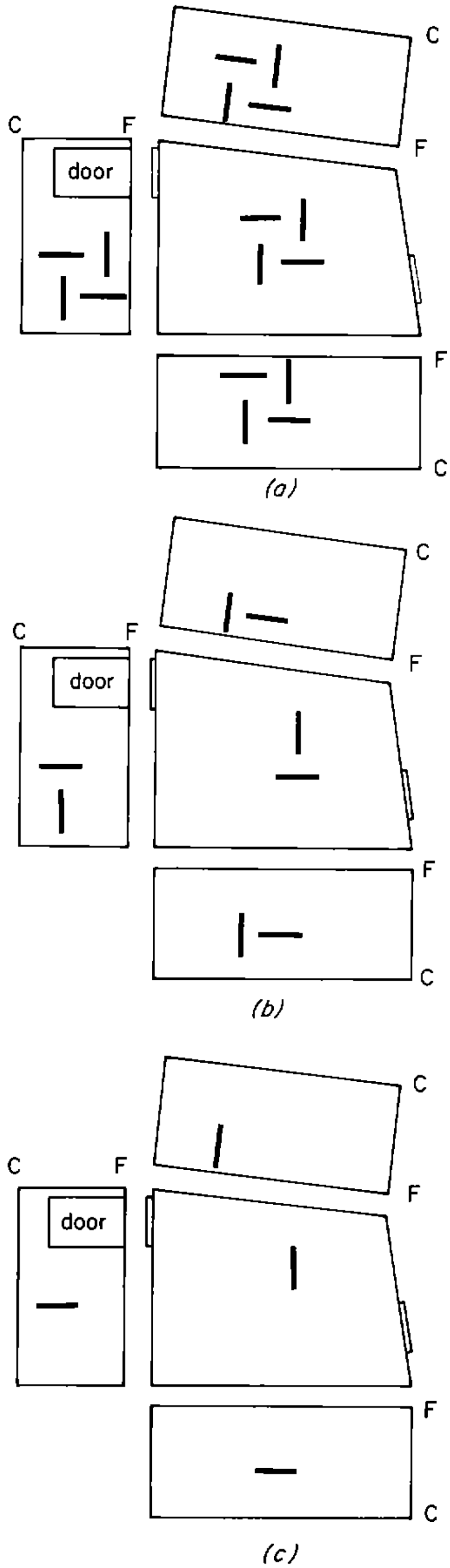

Fig. 4 - Absorbers placed in four groups, with (a) four, (b) two and (c) one absorber per group.
F - Floor level. C - Ceiling level.

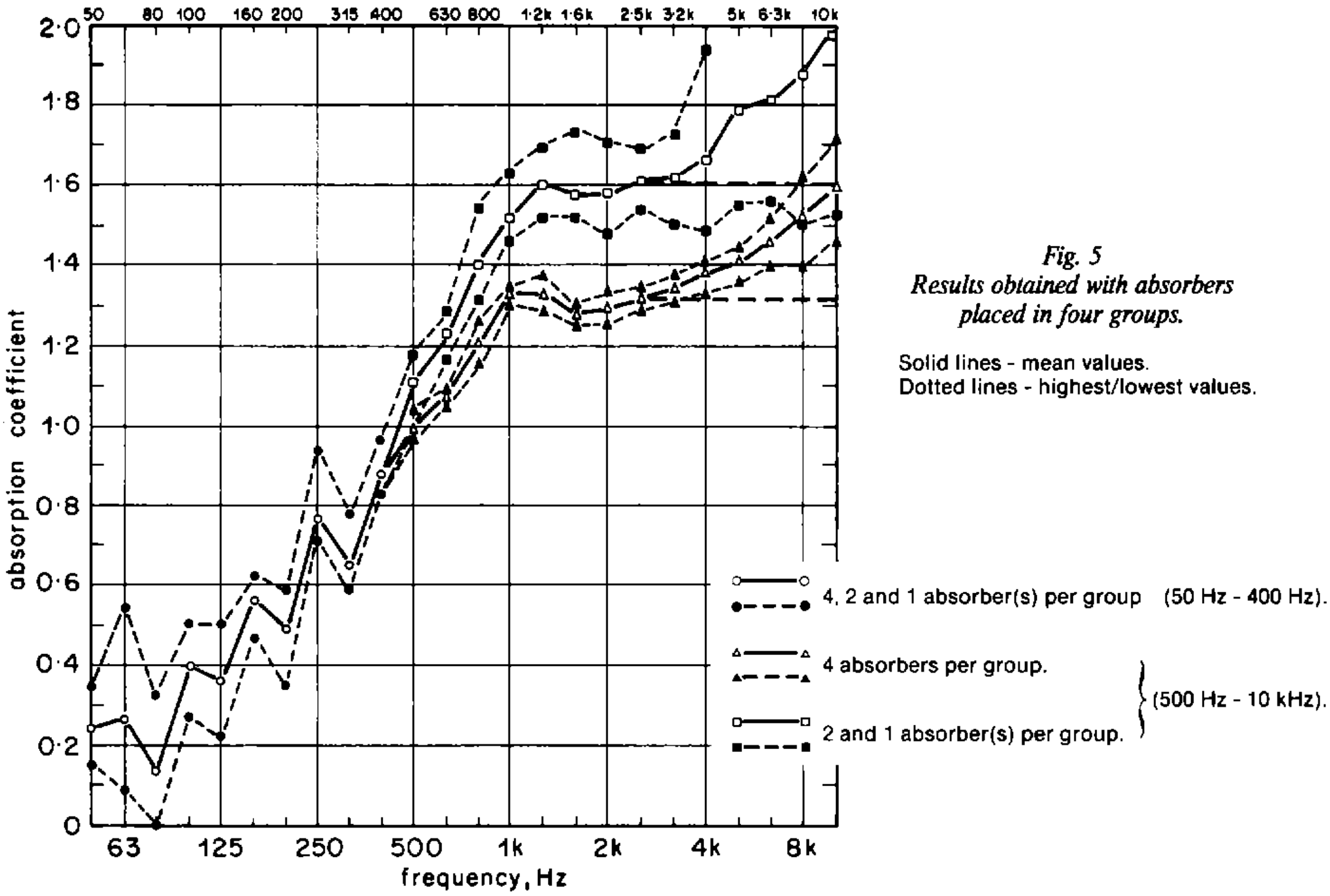

Fig. 5
Results obtained with absorbers placed in four groups.

Solid lines - mean values.
Dotted lines - highest/lowest values.

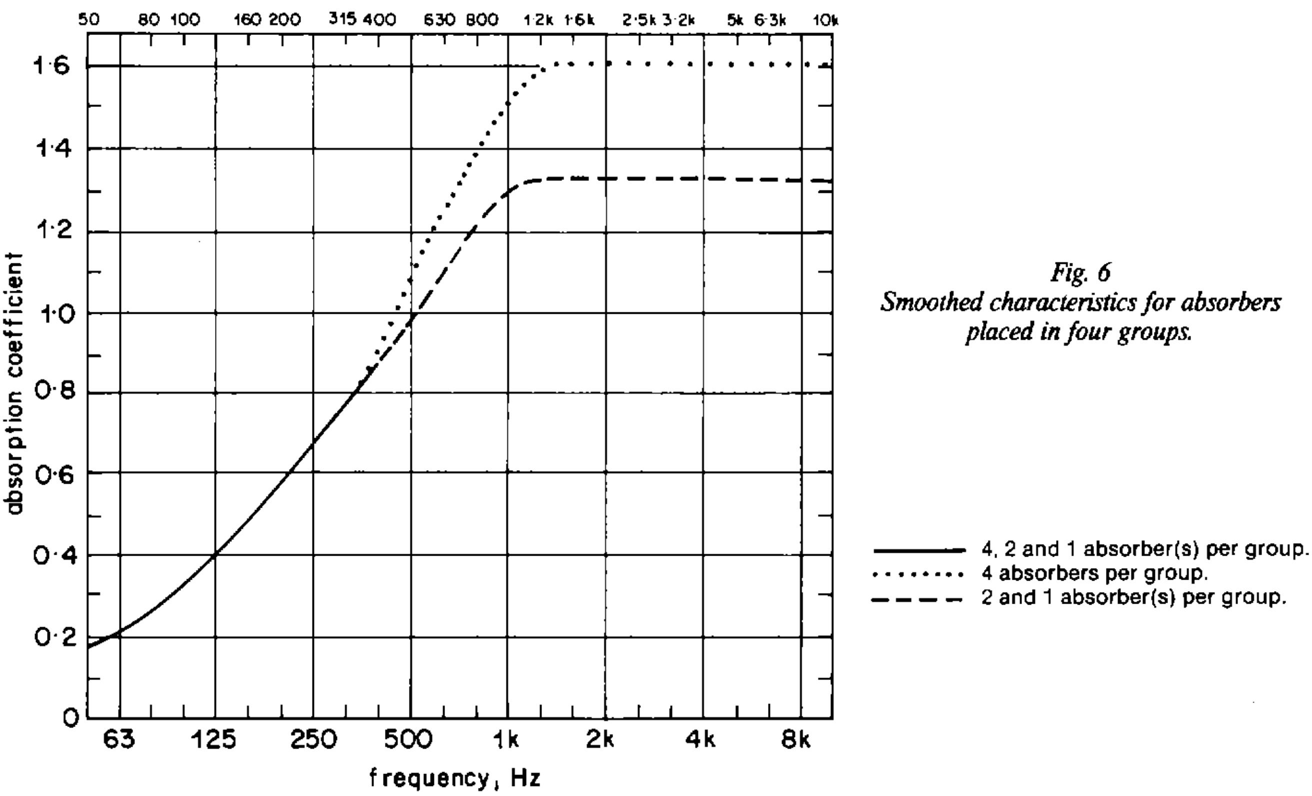

Fig. 6
Smoothed characteristics for absorbers placed in four groups.

3.2 Tests with sixteen absorbers in one large group

All sixteen functional absorbers were placed on the floor of the reverberation room, both in a criss-cross pattern (Fig.7(a)) and also with all absorbers in planes parallel to one or other of the two normal reverberation-room walls (Fig. 7(b) and 7(c)). In the case of the criss-cross arrangement tests were made with the long axes of the absorbers vertical as illustrated, and also with the short axes vertical as described in Section 2. For the other conditions only the "long axis vertical" condition was used. Tests were also carried out with the absorbers suspended 600 mm below the ceiling with short axes vertical (see Fig. 2(c)), and arranged in a criss-cross pattern as shown in Fig. 7(d). Fig. 8 shows the mean absorption coefficients obtained under these conditions, together with the highest and lowest values. Again it can be seen that there were considerable differences in absorption coefficients obtained for particular conditions at some frequencies, but that in general terms the absorption coefficient increased steadily with frequency, the gradient of the characteristic being greatest at mid-frequency. This is shown by the smoothed characteristic (chain-dotted line in Fig. 8). It may be noted that the rise in maximum absorption coefficient value which peaks at 100-125 Hz was produced by the criss-cross arrangement of absorbers standing on the floor with their short axes vertical, while the similar rise with a peak at 2 kHz was produced with the absorbers suspended from the ceiling, again with the short axes vertical. The occurrence of these regions of enhanced absorption shows again how absorber performance can be affected by details of construction and positioning: a detailed investigation of these effects was not, however, attempted.

Fig. 9 shows a comparison of the smoothed versions of the behaviour of the absorbers when arranged in patches of four, two and one (Fig. 6) and the absorbers arranged in one group of 16 (Fig. 8 chain-dotted line). The reduction in absorption coefficient as the number of absorbers in a group is increased is evident: this is most likely caused by the increased screening of an absorber by its neighbours in the group under such conditions. This point is borne out by the results of a further test, in which the absorbers were arranged close together on the floor, long axis vertical, in two groups of eight, as shown in Fig. 10. The absorption coefficients obtained from this arrangement are shown by the crosses and the smoothed curve (double chain-dotted line) in Fig. 9 (note that the high-frequency rise has been ignored: see Section 3.1). It can be seen that for a given frequency the absorption coefficient values are lower than when the sixteen absorbers are spread out to occupy the whole floor.

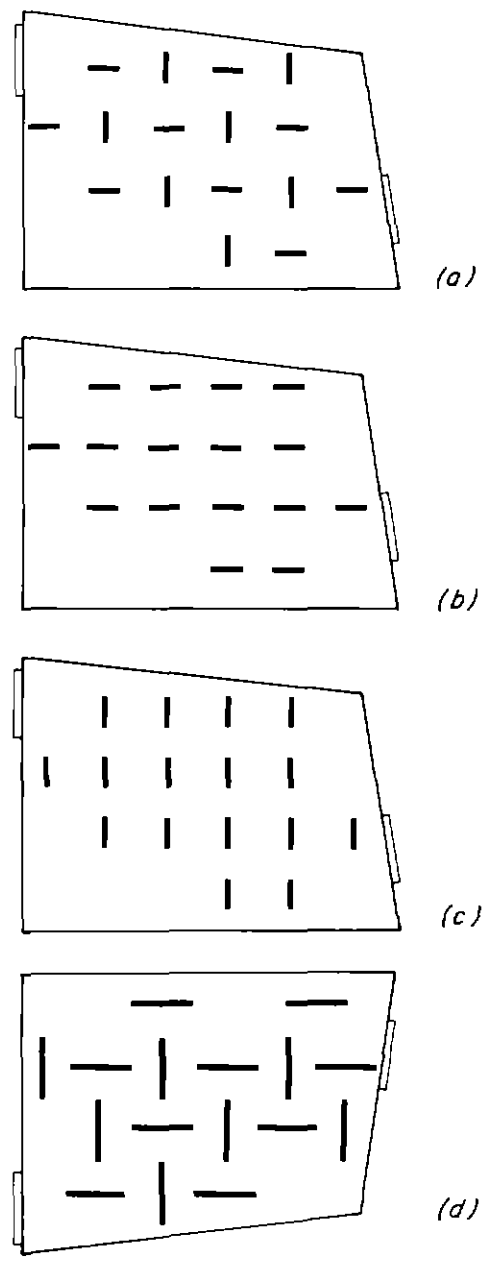

Fig. 7 - Absorbers placed in one large group.

(a) Criss-cross arrangement
(b) In lines along long room dimension } on floor.
(c) In lines along short room dimension
(d) Criss-cross arrangement hanging from ceiling.

Fig. 11 shows a comparison of the behaviour of the functional absorbers arranged in one group of sixteen with the same absorbers again arranged in one criss-cross pattern with the same grid dimension of 1.2 m, but this time lying flat on the floor of the reverberation room. The absorption coefficients obtained under the latter conditions are always lower than those found when the absorbers are used in a "functional" arrangement. This shows the effectiveness of the use of the functional technique in providing absorption when the surface area which can support acoustic treatment is limited. The fact that the difference in absorption coefficient found for the "flat"

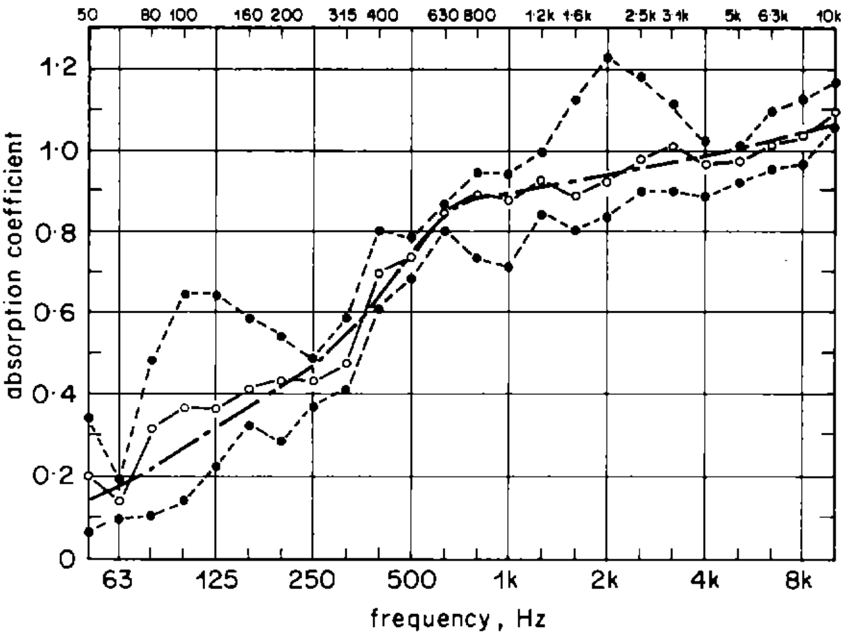

Fig. 8
Results obtained with absorbers placed in one large group.

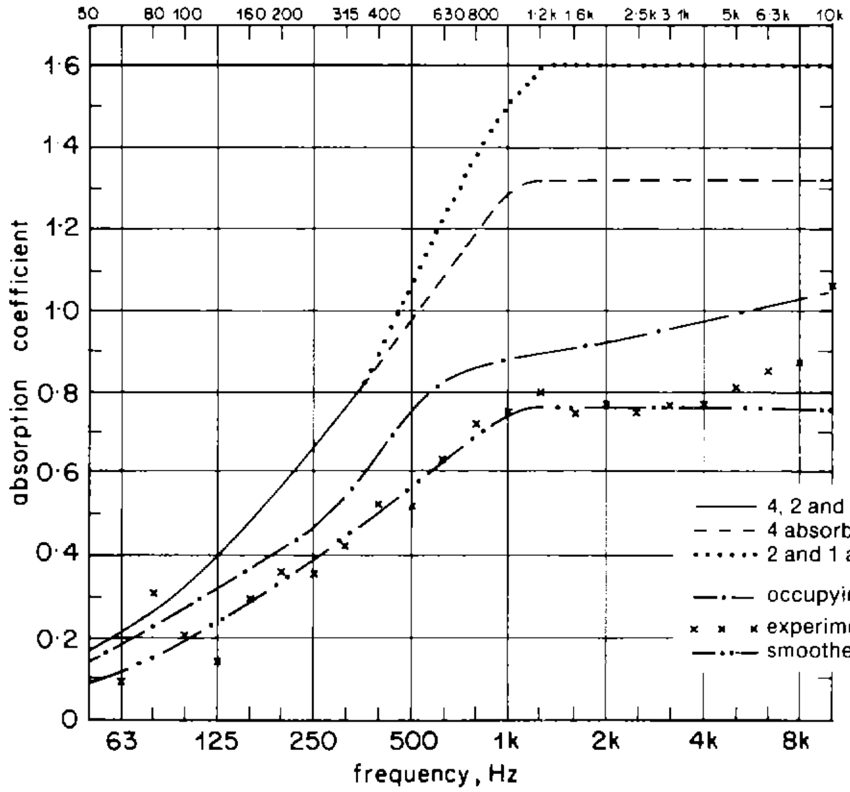

Fig. 9
Comparison of absorption characteristics.

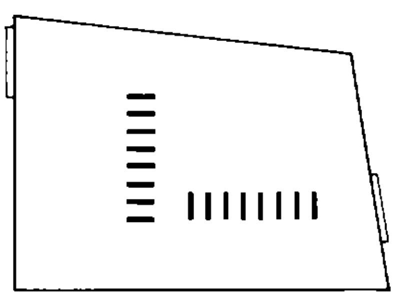

Fig. 10 - Absorbers placed in two close-spaced groups.

and "functional" treatments is at a minimum around 500 Hz, and increases for frequencies both lower and higher than this, sheds some light on the mechanisms of sound absorption that are present: this aspect is discussed in Section 4.1.

3.3 Tests using seven absorbers standing on the floor

The effect of placing absorbers in different positions within a room was tested by arranging seven absorbers, with the long axis vertical, either in straight

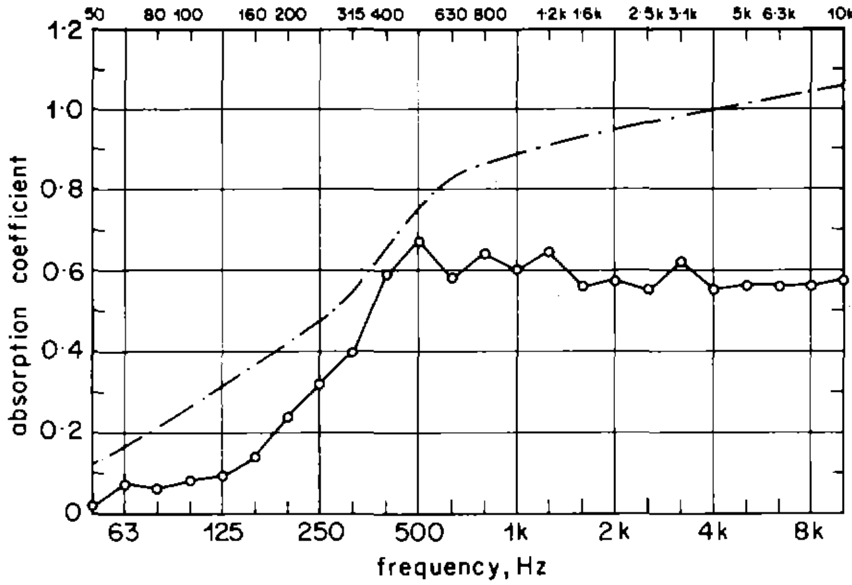

Fig. 11
Behaviour of sixteen absorbers.

lines along the long or the short reverberation-room centre lines (Figs. 12(a) and 12(b) respectively) or alternatively "at random" over the floor (Fig. 12(c)). In fact, this latter arrangement was based on the criss-cross pattern (Fig. 7(a)), care being taken in the removal of the nine "unwanted" absorbers to leave as even a distribution as possible of absorber position and orientation. The number of absorbers used in these tests was set by the ability to form a straight line along the shorter room dimension.

Fig. 13 shows the individual results obtained under each of these conditions, together with the nearest comparable results (using eight absorbers rather than seven) with the absorbers placed in groups of two on four room surfaces (see Section 3.1). The irregular variation of absorption coefficient at low frequencies (both between individual absorber arrangements and between adjacent frequency bands), referred to in Section 3.1, can be clearly seen. Among the three arrangements of seven absorbers, the worst case was a change between values of 0.07 and 0.46 (i.e. a change of over six times) at 80 Hz. Nevertheless, again as before, there is a general tendency for the absorption coefficient to rise with frequency, and a mean curve can be drawn: Fig. 14 shows such a curve (note that this curve refers only to results obtained with seven absorbers standing on the floor) together with highest-value and lowest-value limits. Also shown is a "smoothed" version (chain-dotted line): the rise in absorption coefficient value at the highest frequencies has again been discounted (see Section 3.1).

Although small enough not to preclude taking a mean result as discussed above, it can nevertheless be seen from Fig. 13 that at higher frequencies there are systematic differences in the absorption coefficients obtained using different absorber arrangements. As far

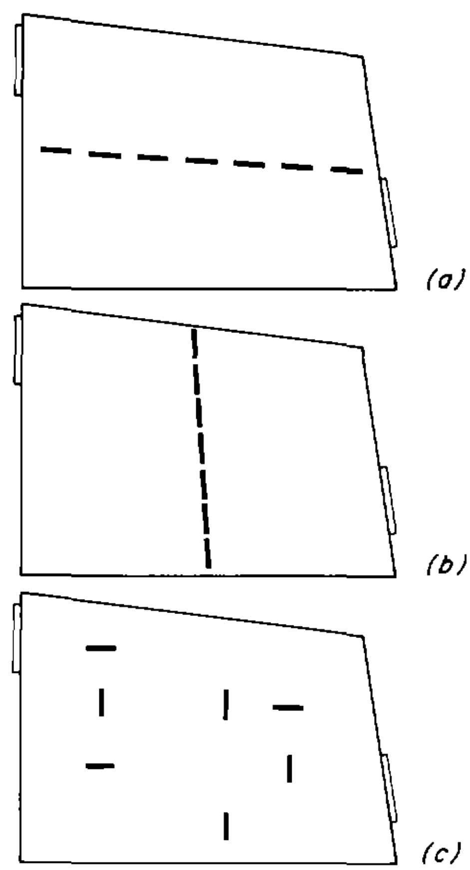

Fig. 12 - Seven absorbers on floor of reverberation room.

(a) In line along long room dimension.
(b) In line along short room dimension.
(c) "Random" arrangement.

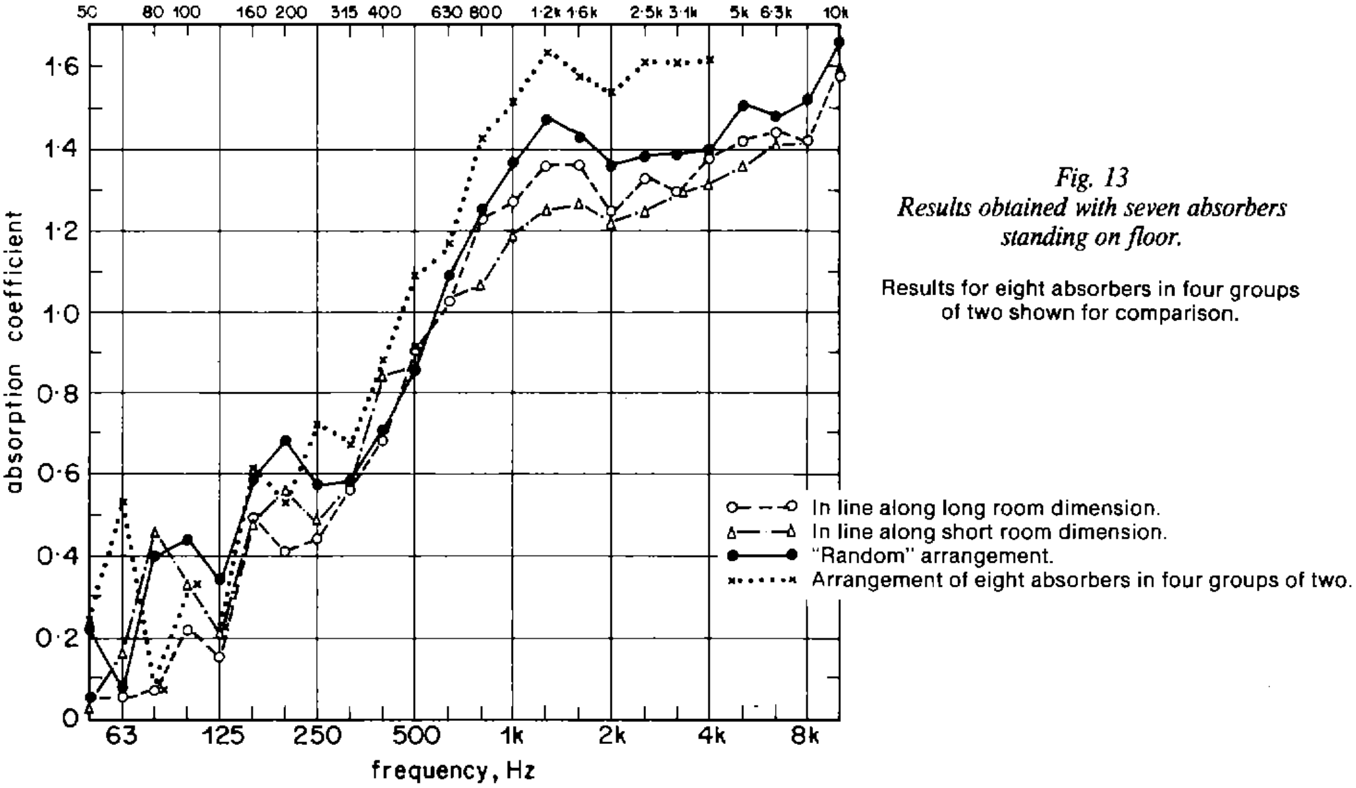

Fig. 13
Results obtained with seven absorbers standing on floor.

Results for eight absorbers in four groups of two shown for comparison.

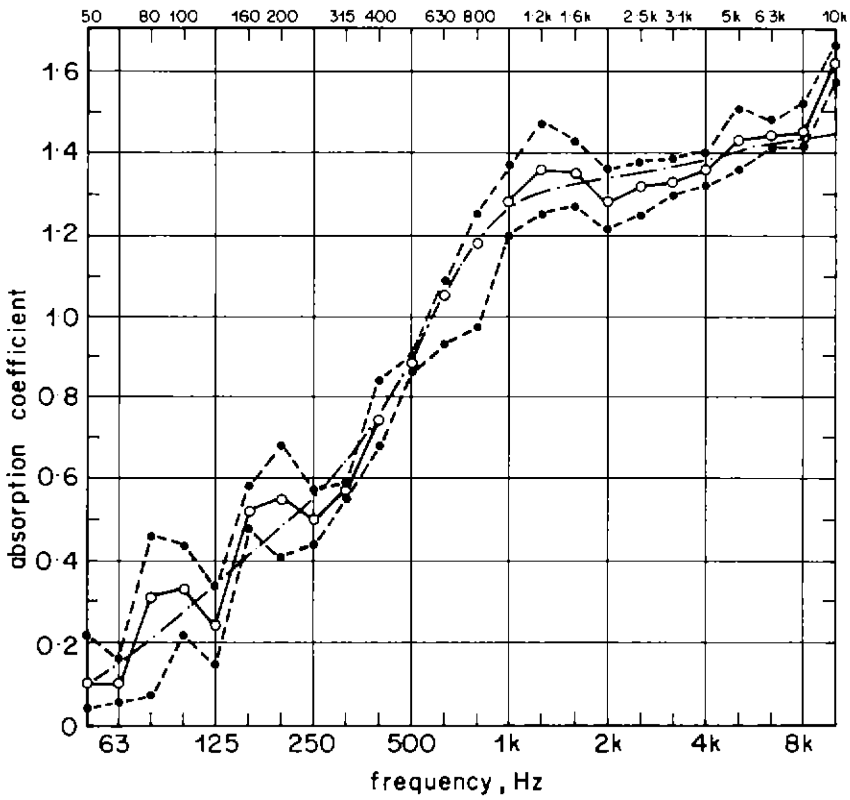

Fig. 14
Average results obtained with seven absorbers standing on floor.

as the absorbers in four groups and the random absorber arrangement on the floor are concerned (dotted and full lines in Fig. 13) this tendency may be attributed to the mutual screening of one absorber by another, the screening being greater when all the absorbers are on one surface. At first sight the results obtained with the absorbers arranged in straight lines (dashed and chain dotted lines in Fig. 13) are not consistent with this explanation, since the absorbers are not "screened" from each other in the usual sense, and yet the corresponding absorption coefficients are lower than those obtained with the "random" arrangement. An insight into this anomaly can be obtained from Fig. 15, which shows the results

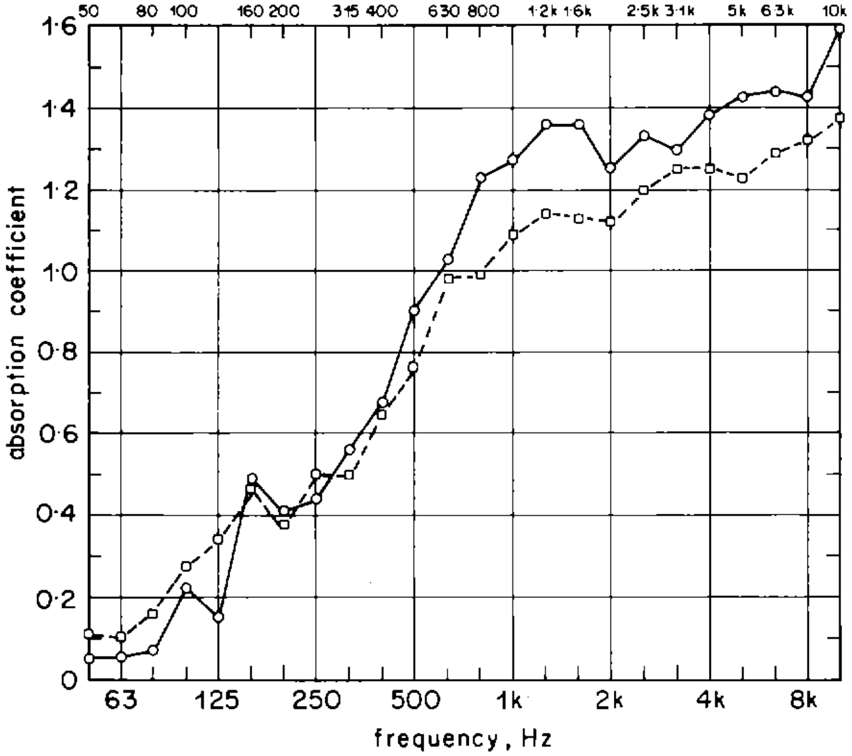

Fig. 15
Results obtained with absorbers in line along long room dimension.

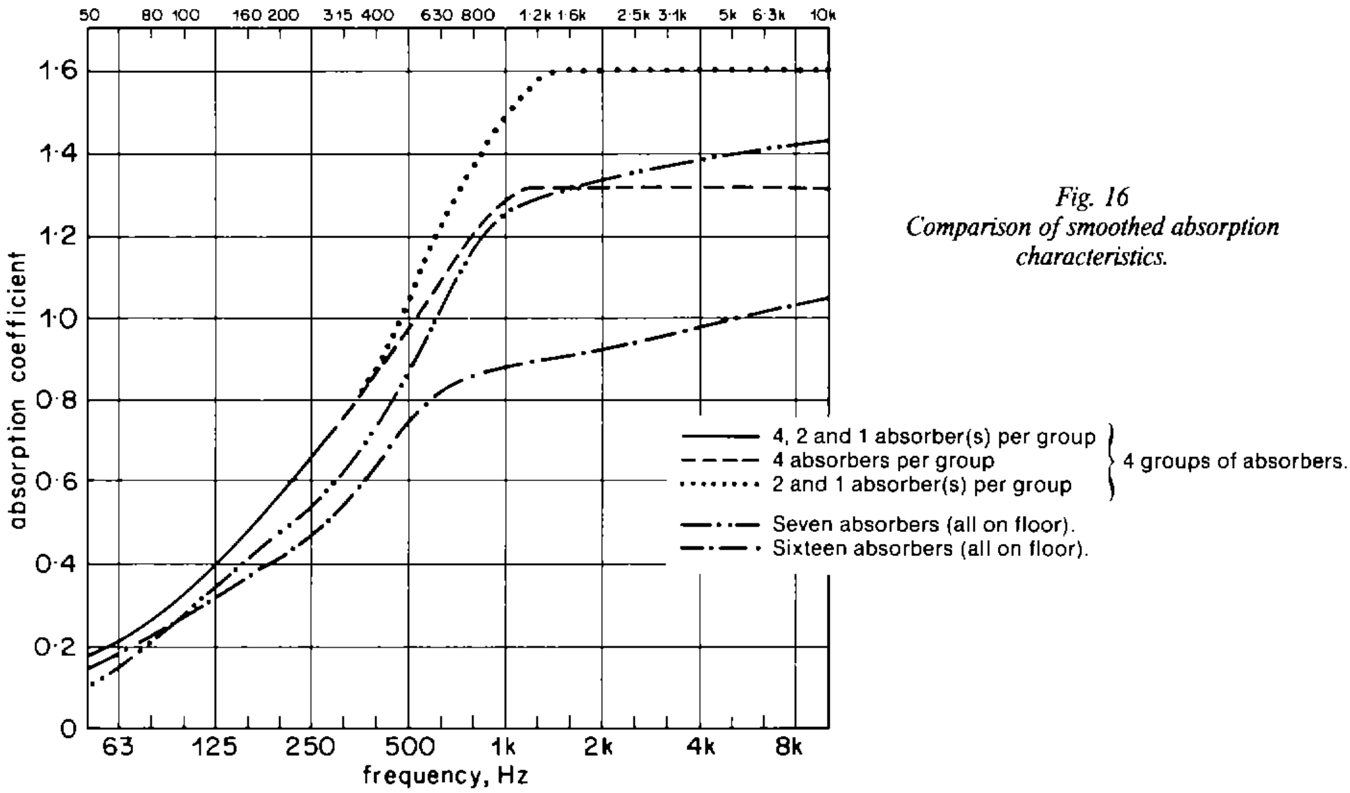

Fig. 16
Comparison of smoothed absorption characteristics.

obtained with absorbers arranged in a straight line along the longer centre-line of the reverberation room, first with seven equi-spaced absorbers, (full line) and then with ten absorbers nearly touching each other (dotted line). It can be seen that the latter condition gives rise to a significant reduction in absorption coefficient. This can be explained in terms of an absorber extracting energy from parts of the sound field which are not immediately in front of it, or, in other words, that the lines of power flow into the absorber are not necessarily normal to its surface[2]. Absorbers placed closer together then have less sound energy available to absorb and the apparent absorption coefficient is, therefore, reduced.

Turning to Fig. 13, it can be seen that absorption coefficients measured when the seven absorbers were in a line along the shorter dimension of the room, and, therefore, as close together as possible (chain-dotted line), were lower than when the absorbers were spaced further apart along the longer room dimension (dashed line) in agreement with this explanation. The argument can be extended to explain the higher absorption coefficients obtained with seven absorbers in the "random" floor arrangement and eight absorbers arranged in four separated groups, in terms of the increased average distance between the absorbers in these cases.

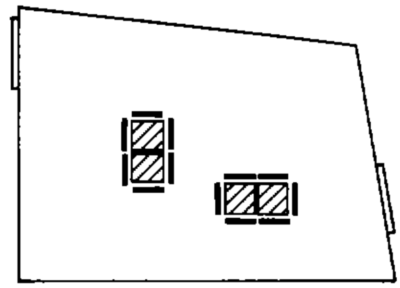

Fig. 17 - "Box" arrangement of absorbers.

Absorber lying on floor shown shaded.

The "smoothed" version of the mean absorption coefficient curve obtained when seven absorbers are present (chain-dotted line in Fig. 14) is compared in Fig. 16 with the smoothed characteristics obtained as described in Sections 3.1 and 3.2, with sixteen absorbers present. It can be seen that under all conditions where the absorbers are well spaced from one another, at least in a direction normal to their surface, their behaviour is similar up to a frequency of around 315 Hz. Above this frequency the absorption coefficient starts to depend more strongly on the particular arrangement of absorbers within the room: in general terms, the more the absorbers are clustered together into groups, the more the absorption coefficient is reduced.

3.4 Tests with groups of eight absorbers arranged in a box formation

Suspended panels of absorbing material are sometimes used in an arrangement in which the panels are hung in an enclosure lined with more absorbent material, one side of the enclosure being open to the studio. In the present tests it was not possible to reproduce this arrangement exactly with the materials available, but an approximation to it was set up in which seven of the experimental panels of absorbing material, with long axes vertical, were formed into a double box arrangement on the floor of the reverberation room, an eigth absorber being placed flat on the floor to form an absorbent layer at the bottom of the boxes. Two such assemblies were used to form the complete test configuration, as shown in Fig. 17. In this arrangement, the panel which divided one box of each assembly from the other represented the suspended panel, while the other panels represented the lined enclosure. To minimize absorption on the outside of these latter panels, the outer surfaces were covered with sheets of hardboard. The absorption characteristics of such an arrangement are shown in Fig. 18. It can be seen that much the same trend of absorption coefficient with frequency is obtained, as compared with the use of other arrangements described in this Report. The lower absolute values of absorption coefficient occur because of the screening of one side of most of the absorbing panels either by the hardboard panels or (in one case) by the floor of the room, as well as the mutual screening of one absorbing panel by another.

Measurements were also made using this absorber arrangement but without the hardboard covering panels in place (Fig. 19, full line). This may be compared with the closely-spaced in-line arrangement described in Section 3.3 (see Figs. 9 and 10): the results from this latter arrangement are also shown in Fig. 19 (dashed line). Fewer absorbing panels suffer from mutual screening (at least on one face) with the box arrangement, and at higher frequencies this accounts for the increase in measured absorption coefficient compared with the in-line arrangement. As noted before (Section 3.1), it is difficult to infer general absorber performance at low frequencies from the results of individual tests: nevertheless it is not unreasonable to expect that "deep treatment" of this kind, applied to a relatively large wall area, would give useful absorption extending down to relatively low frequencies, as is suggested by the enhanced low-frequency absorption shown by this arrangement. It may be noted that such deep treatment, often in the form of wedges of absorbing material, is commonly used in the construction of anechoic chambers where the greatest possible absorption at all frequencies is required. There is no evidence to suggest, however, that such treatment will give absorption predominantly in the low- or mid-frequency ranges.

3.5 The effect of loading the absorbing panels with welded steel grids

Tests on nine absorber configurations were carried out with the mineral wool absorbing blanket supported with grids of welded steel rods on each side of the blanket, and were then repeated without such supports in place. Details of the test conditions are shown in Table 1, and the differences in absorption coefficient obtained when the steel grids were present (α_w) and absent (α_o) are plotted in Fig. 20 (to avoid

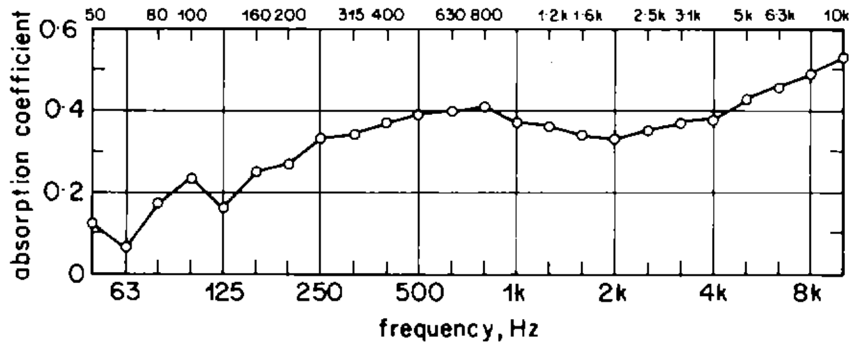

Fig. 18
Results obtained with absorbers in box arrangement, with exterior cladding of hardboard.

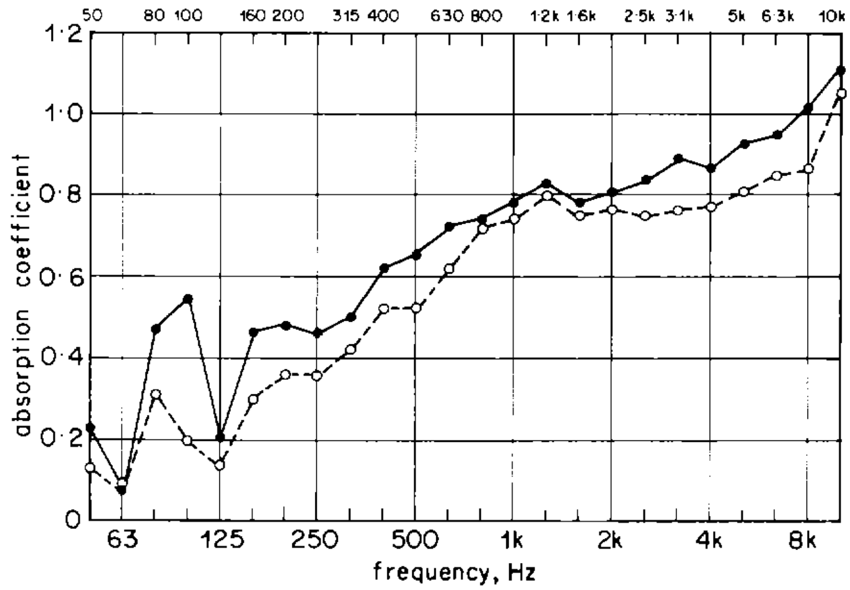

Fig. 19
Results obtained with absorbers in box arrangement, without exterior cladding of hardboard.

Results for close-spaced in-line arrangement shown for comparison.

Box arrangement.
In-line arrangement.

confusion, lines joining the plot points for particular absorber arrangements have been omitted). It can be seen that although there is considerable scatter in the results obtained at each frequency, there is nevertheless a tendency for the absorbers loaded with the steel grids to have a higher absorption coefficient than those without this loading. This trend is shown more clearly in Fig. 21, which shows the mean change in absorption coefficient for each frequency, together with limit lines corresponding to twice the standard error of the mean. These limit lines, which indicate the range of values of absorption coefficient difference within which there is a 95% probability that the mean value of another nine sets of measurements would fall, are conventionally regarded as an indication of the expected measurement uncertainty. (This assumes that the individual measurements conform to certain statistical rules, including the assumption that they all belong to the same "universe" of such measurements: in other words, that factors such as the size and shape of the absorbers and the geometry of the room in which they are situated are similar). It can be seen from Fig. 21 that for frequencies between 80 Hz and 500 Hz the mean values of absorption coefficient obtained with the steel grids in place were significantly greater, on average, than those formed without using the grids, although Fig. 20 shows that at all frequencies the converse was true, or the two measured absorption coefficients were equal, for some individual measurements. In making the measurements it was found that arranging that the mineral wool layer was in contact with the supporting grids over its entire surface (for example by pulling the grids together at several points using a fastening passing through the mineral wool) significantly increased the sound absorption. The increase in absorption is roughly 20% of the value obtained without the use of the steel grids and is perhaps not of great significance in acoustic terms: its main interest is in the insight it gives into the mechanism of sound absorption at these frequencies, as discussed in Section 4.1.

Measurements were also carried out with and without the steel grid supports with the absorbers lying flat on the floor (see Section 3.2). In this case there was no significant difference between the results obtained on the two occasions.

4. DISCUSSION

4.1 Mechanisms of absorption in a functional absorber

Sound energy in a reverberant enclosure consists of two components: potential energy and kinetic energy. For any one particular room mode,

Table 1: Conditions used for tests without and with welded steel grid supports

Absorber arrangement			Plot point in Fig. 20	Reference	
Position(s) in room	Number used, and arrangement	Axis normal to room surface		Section	Fig.
4 patches on 3 walls and floor	4 per patch	short	●	3.1	4(a)
	4 per patch	long	○	3.1	
	2 per patch	short	▲	3.1	4(b)
	2 per patch	long	△	3.1	
	1 per patch	short	■	3.1	4(c)
	1 per patch	long	□	3.1	
on floor	7 along long axis	long	×	3.3	12(a)
	7 along short axis	long	+	3.3	12(b)
	7 random	long	*	3.3	12(c)

potential sound energy occurs at regions of maximum sound pressure: in such regions sound pressure changes very little with position in the sound field, and the air velocity can be considered as zero. On the other hand, kinetic sound energy occurs at regions of maximum air velocity*. Here the change in sound pressure with position in the sound field is at a maximum, while the sound pressure itself is small and can be considered as zero. (Strictly speaking this is true only at the actual point of maximum air velocity, and then only if no sound absorption takes place at the surfaces of the enclosure, so that there is no "travelling" energy component from the sound source to these surfaces). If many room modes are excited simultaneously, energy at any point in a room will consist of both potential and kinetic components. An exception to this generality is to be found immediately in front of a reflecting surface, where "boundary conditions" dictate that the air velocity is zero: pressure maxima, therefore, occur in front of all such surfaces.

Sound absorption in porous material occurs when air passes through it, and power is dissipated by viscous drag in the pores. In the case of material backed by a hard surface, sound pressure at the free surface forces air into the pores, where absorption takes place. Absorption is, therefore, greatest when the absorber is near a sound pressure maximum, or in other words in a region where the potential energy component of the sound field predominates[2] (Fig. 22(a)).

* In acoustics it is usual to consider volume velocity (in units of cubic metres per second).

Absorption rises as the sound wavelength decreases in relation to the thickness of material, and porous blankets are, therefore, more absorptive under these conditions at higher frequencies. If, as in the case of the functional absorbers discussed in this Report, the absorber is exposed to the sound field on both sides in a region of potential sound energy (Fig. 22(b)), air will be forced into the pores on both sides. A "neutral plane" of zero sound pressure will form at the midpoint of the blanket, and the absorber will behave as a blanket of half the thickness and twice the area, relative to the arrangement of Fig. 22(a).

Air velocity† will be high in a region of the sound field where the kinetic energy component predominates. If a sheet of porous material is placed normal to the direction of air flow in such a region (Fig. 23(a)), sound power will be dissipated because of air flow through the material and sound absorption will then occur (this assumes that the flow resistance of the material is low enough so as not to be the controlling factor in determining the air velocity). If, however, the sheet of material is placed parallel to the direction of air flow (Fig. 23(b)), no air will flow through it and no absorption will occur. In the present tests these effects are likely to be significant at low frequencies, where the absorber thickness is very small compared with sound wavelength.

† The terms "air velocity" and "air flow" must not be thought of as implying a unidirectional flow of air: the concern here is with the alternating component of flow which represents the kinetic energy component of the sound field.

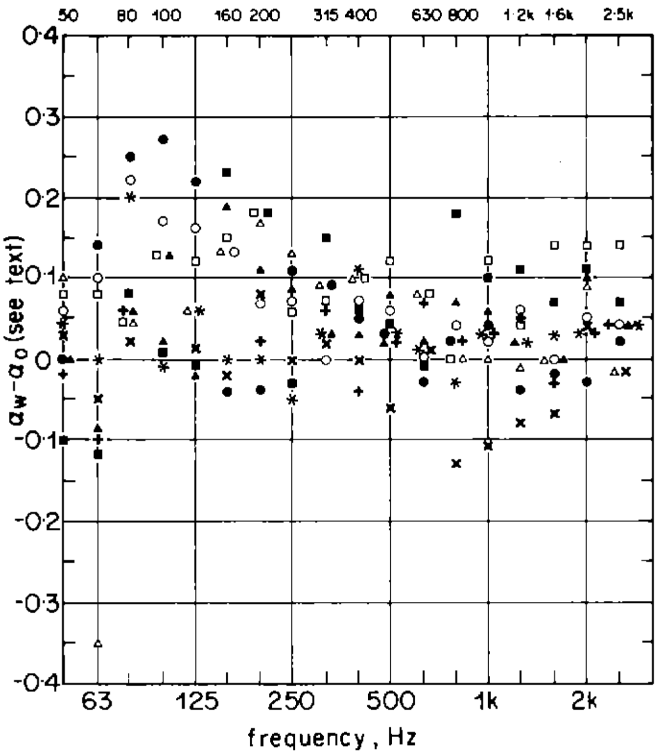

Fig. 20 - Effect on absorption coefficient of supporting absorbing blanket with grids of welded steel rods.

Details of plot point symbols are shown in Table 1.

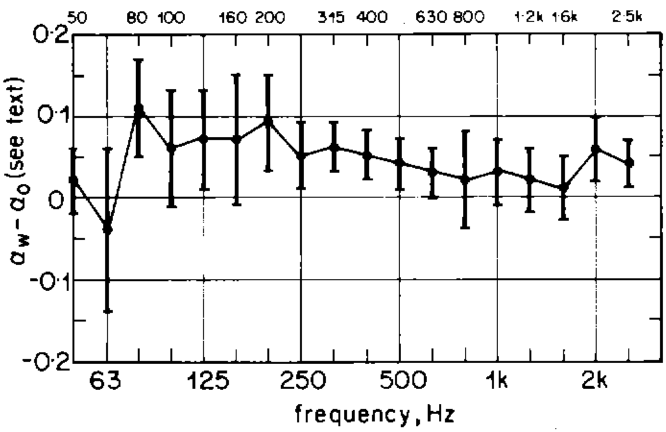

Fig. 21 - Mean change in absorption coefficient caused by presence of steel grid supports.

Bar lines show ± twice standard error of mean values.

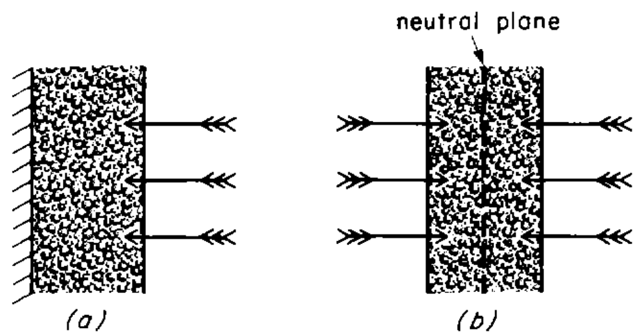

Fig. 22 - Porous absorber in a region of potential sound energy.

(a) Backed by hard surface.
(b) Exposed to sound field on both sides.
Arrows show direction of air movement.

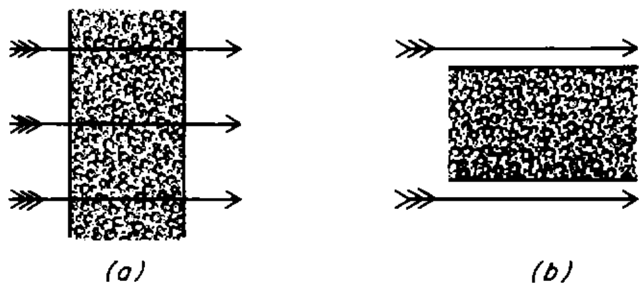

Fig. 23 - Porous absorber in a region of kinetic sound energy.

(a) Plane of absorber normal to direction of air velocity.
(b) Plane of absorber parallel to direction of air velocity.
Arrows show direction of air movement.

Supporting a panel of porous material with grids of welded steel rods, as described in Section 3.5, increases its surface density without significantly changing its flow resistance. The resulting effect on the absorption coefficient of the panel, when it is situated in a region of high air velocity, may conveniently be examined using the technique of representing mechanical parameters by electrical equivalents. Fig. 24(a) shows the equivalent circuit of the absorber without extra loading, M_A representing the surface density of the material and R its flow resistance. The air volume velocity U divides into two components U_M and U_R "flowing" though M_A and R respectively as shown in the phasor diagram (Fig. 24(b)), and causing a sound pressure Δp to appear across the absorber. Assuming that the nature of the porous material is such that the impedance of M_A is low compared with that of R at the frequency in question, U_R is small compared with U_M and only a small amount of power is dissipated. When the surface density is increased, however (Fig. 25(a)), the value of the mass component is increased (shown by the "extra" surface density M_L in series with M_A) and the partition of velocity in the two branches of the circuit changes, so that the component "passing through" R increases (Fig. 25(b)). The power dissipated in R, and, therefore, the absorption coefficient, thus increases. In physical terms, a lightweight porous blanket will tend to vibrate under these conditions, diminishing the velocity of the air passing through it and therefore reducing the sound absorption. As the surface density of the blanket is increased, there will be less tendency for it to vibrate, and sound absorption will be enhanced by the resulting increase in the velocity of air passing through it.

In the case of the absorber lying flat on the floor, as discussed in Section 3.5, the conditions which exist at a region of potential sound energy should be considered. Here (Fig. 26) the sound pressure p forces air into the absorber against the compliance C of the entrapped air. The mass of the porous blanket (M_A) is swamped with the very large mass of the floor itself

(M_S), and the sound velocity components U_M and U_R are not significantly affected by further panel loading (M_L). Because of this, the extra loading does not in this case give rise to an increase in absorption.

It may be noted that the above analysis, using "lumped" values for the various impedances associated with a porous absorber, represents a greatly simplified treatment of the subject: a more detailed account is given elsewhere[3]. Nevertheless, the analysis gives an explanation for the increase in absorption coefficient

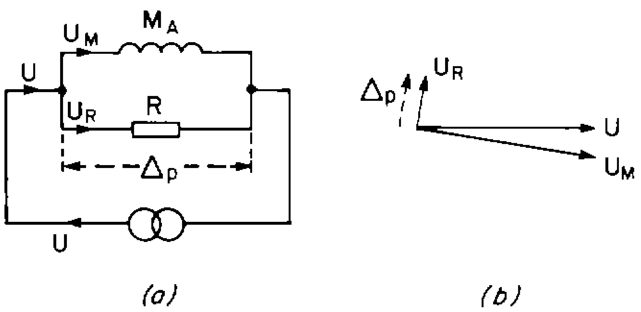

Fig. 24 - Electrical analogue of porous absorber in kinetic sound field.
(a) Equivalent circuit.
(b) Phasor diagram.

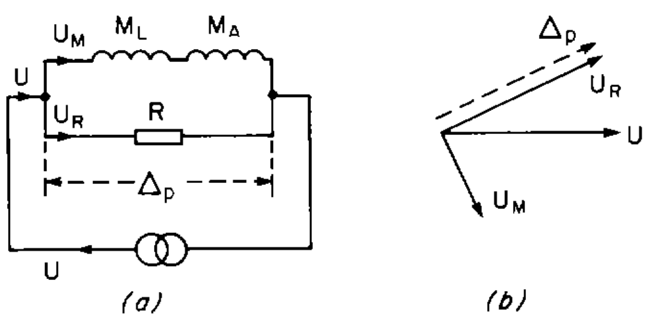

Fig. 25 - Effect of increasing surface density of porous absorber in kinetic sound field.
(a) Equivalent circuit.
(b) Phasor diagram.

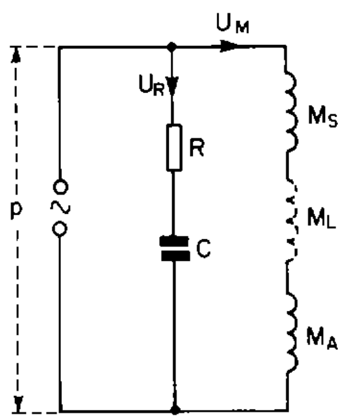

Fig. 26 - Electrical analogue of porous absorber in potential sound field, backed by hard surface.

produced when a lightweight "functional" absorber panel is loaded with relatively massive steel grids on each side, as described in Section 3.5.

In general terms, the mechanism of sound absorption that takes place in a functional absorber can be considered in three frequency bands. Below about 250 Hz the absorbers appear to be sensitive, at least to some extent, to the kinetic component of the sound field, as shown by the increase in absorption which is obtained when the strengthening panels of steel rods are added. This accounts for the extreme variability of the absorption coefficient values obtained in individual frequency bands using different absorber configurations, as these configurations are likely to react in different ways to the mode structure present in the reverberation room. Above 1 kHz the absorbers are sensitive to the potential component of the sound field, behaving as porous panels of half the thickness and twice the surface area (compared with their actual dimensions) backed by a massive rigid surface. The two octaves between 250 Hz and 1 kHz may be regarded as a transitional region between these two modes of operation.

4.2 Comparison with other work

Cops[4] has measured the absorption of both flat and cylindrical functional absorbers arranged in a number of configurations. There are unfortunately some difficulties in interpreting the results presented in this paper, because of ambiguities in both the descriptions of the absorber arrangements, and also the values of absorber area used in the absorption coefficient calculations. The results shown in Figs. 27 and 28 have been adjusted (according to the present author's interpretation of this paper) so as to use actual absorber area for this purpose, as discussed in Section 2 of this Report. Furthermore, Cops uses the simple formula

$$\alpha = \frac{0.16V}{S}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \qquad (4)$$

where V, S, T_1 and T_2 are respectively the room volume, absorber area, and the reverberation times of the full and empty reverberation room, to derive absorption coefficient values. This formula is based on the Sabine relationship between absorption coefficient and reverberation time, and gives coefficients which are numerically too high, especially when the coefficient itself is large: in addition, air absorption is ignored. Nevertheless, the general agreement in the shape of the absorption characteristic between the results obtained by Cops and the results described in this Report can be seen from Figs. 27 and 28. Cops used panels with dimensions 1.2 m x 0.6 m, as in the present work, but his blanket of absorbing material

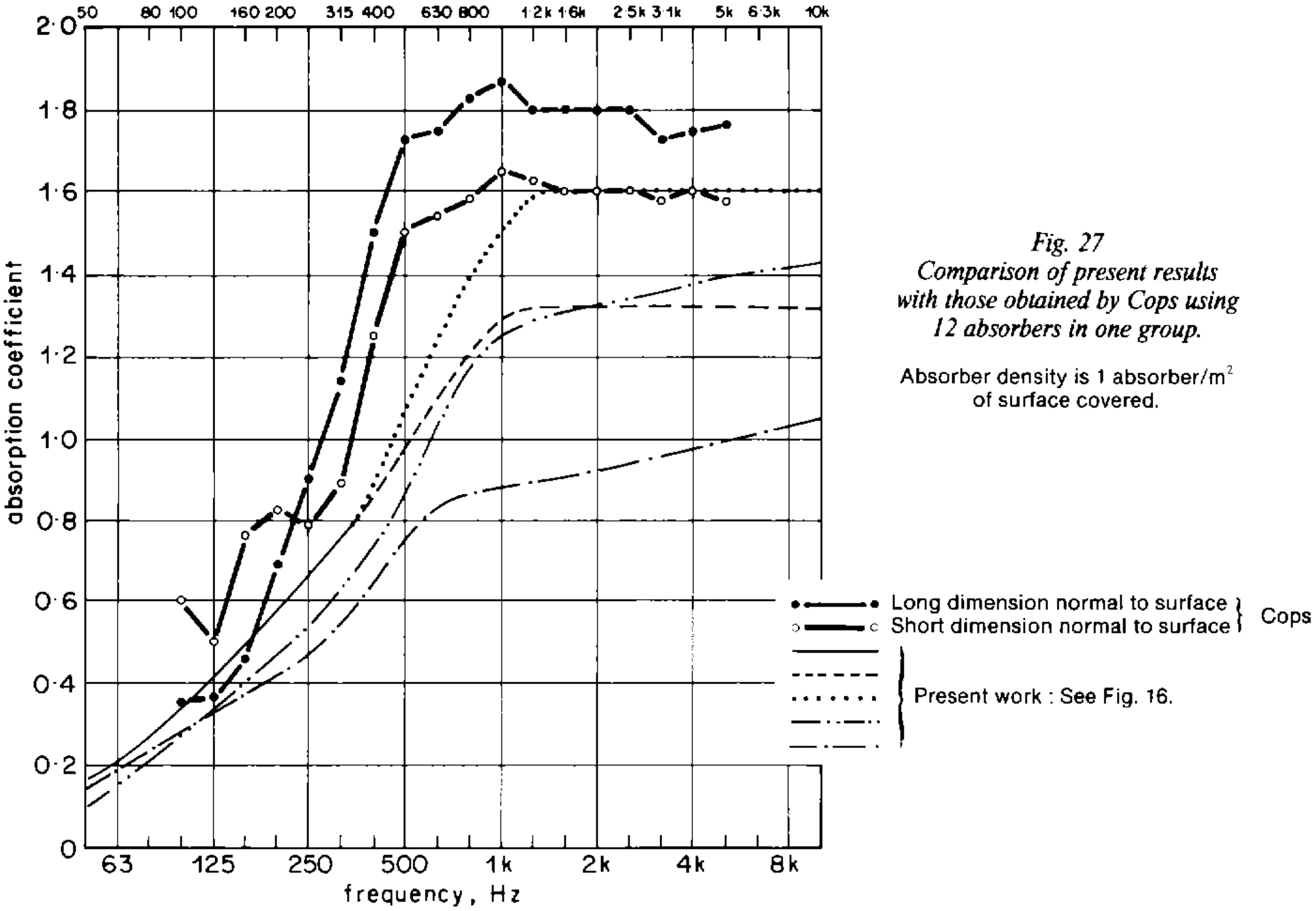

Fig. 27
Comparison of present results with those obtained by Cops using 12 absorbers in one group.

Absorber density is 1 absorber/m^2 of surface covered.

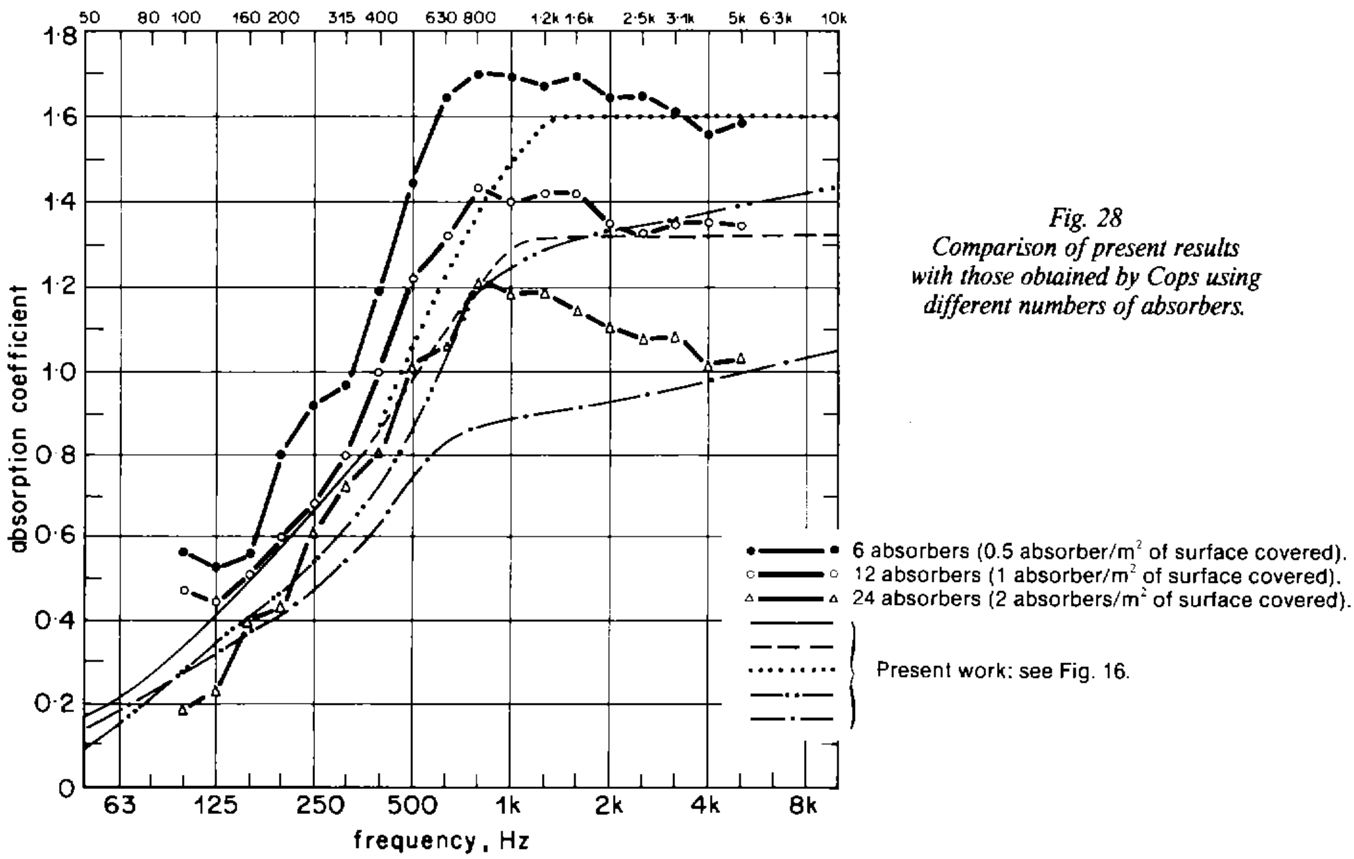

Fig. 28
Comparison of present results with those obtained by Cops using different numbers of absorbers.

was thicker, being 80 mm and 50 mm for the results shown in Figs. 27 and 28 respectively. This probably accounts for the steep rise in absorption taking place at a lower frequency than in the present results, which is particularly apparent in Fig. 27. Cops found a difference between the use of absorbing panels with either long or short dimensions normal to the supporting surface, whereas the present results showed no significant differences in these cases. Possibly this was due to the method of mounting the absorbers, as Cops surrounded his absorber group with a hard reflecting screen. The reduction in absorption coefficient as the number of panels in a given area is increased is apparent from Fig. 28. In relative terms this is in agreement with the present results. Recalling, however, that the present results were obtained with an absorber density of 0.7 per square metre, and that the results for one large patch of this density are shown by the chain-dotted line in Fig. 28, it can be seen that the absorption coefficient values obtained by Cops were considerably higher, for equivalent (as near as possible) absorber arrangements. Not all this difference can be accounted for by the differing methods of absorption coefficient calculation: it may be relevant that Cops used a much larger reverberation room (193 m^3) than was the case in the present work.

Orlowski[5] has carried out tests in a model reverberation chamber similar to that used by Spring in 1971[6], but using a 16:1 scaling factor. This chamber had an actual volume of 0.39 m^3: thus at the scale frequencies the volume becomes $(0.39 \times 16^3) =$ 1597 m^3. The "model" test panels were square, of scale size 1 m, being made of felt 4 mm thick and thus having a scale thickness of 64 mm. This material was chosen as having (to the appropriate scale) the same absorption characteristics as 100 $kg.m^{-3}$ mineral wool with a thickness of 75 mm, measured in both cases when lying on the floor of the appropriate reverberation room: it did not necessarily have the same flow resistance characteristics, however, when freely suspended. Fig. 29 shows a comparison of

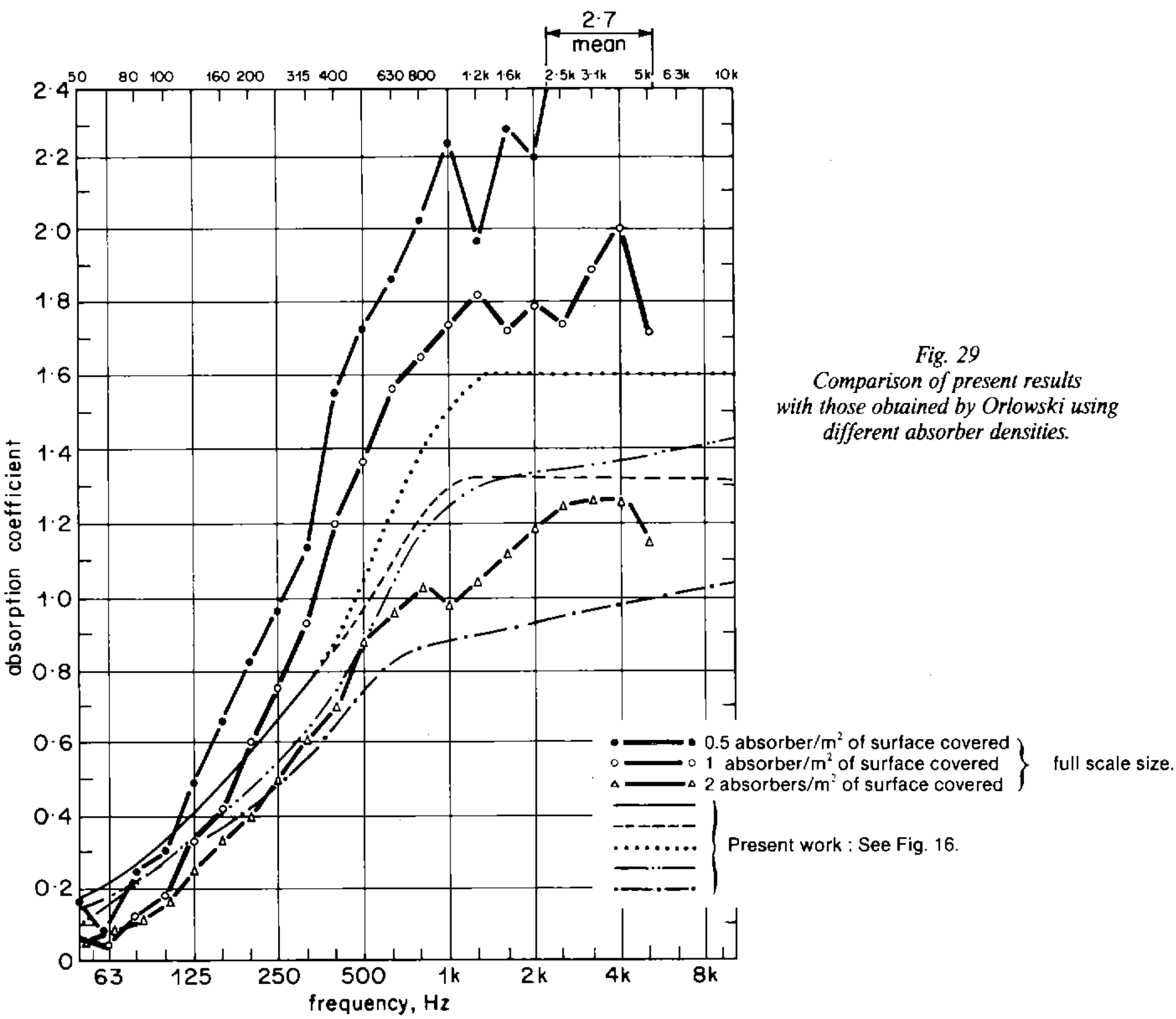

Fig. 29
Comparison of present results with those obtained by Orlowski using different absorber densities.

absorption coefficients obtained using this modelling technique with the results of this present investigation. The model absorbers were suspended in a criss-cross pattern, at scaled densities of 0.5, 1 and 2 absorbers per square metre (fortuitously the same as in the experiment carried out by Cops). The increase in absorption coefficient with decrease in the number of absorbing panels in a given area can again be seen: however, the values of the absorption coefficients at higher frequencies are, for comparable test conditions, even higher than those obtained by Cops. Orlowski used a set of diffusing panels, hung in the body of the reverberation chamber below the absorbing panels, which may have enhanced the measured absorption coefficients by directing sound energy towards them. However, the volume of the reverberation room used for the tests may also be relevant: he used a room some eight times the volume (when appropriately scaled) of the one used by Cops, and 15 times the one used in the present work. This observation that the measured absorption coefficient appears to increase with increase of room volume is in agreement with work carried out by Harwood, Randall and Lansdowne[7].

5. CONCLUSIONS

Functional absorbers, or in other words panels of porous material arranged to project from the surfaces of a room, show in general a rising characteristic of absorption coefficient against frequency up to a certain value (typically 500 Hz - 1 kHz), above which the absorption coefficient remains constant.

At the lower frequencies (say below 250 Hz) absorption appears to take place, at least in part, because the velocity (kinetic) component of the sound field causes air to pass through the absorber where power is dissipated by viscous friction. In this context, increasing the surface density of the absorber without altering its thickness or porosity, by loading it with relatively massive but acoustically transparent material (sheets of welded steel rods, for example), gives on average an increase of absorption coefficient of about 20% at these lower frequencies. At the higher frequencies (say about 1 kHz) absorption is mainly due to the potential (pressure) component of the sound field, which forces air into the surface layers of the absorber, against the compliance of the entrapped air, so that power is again dissipated by viscous friction. A neutral plane of zero velocity exists at the centre of the absorber, which behaves as if it had twice its actual surface area and half its thickness, backed by a massive rigid surface. The frequency range 250 Hz - 1 kHz may be regarded as a region of transition between these two mechanisms of sound absorption.

The absorption coefficient of an individual absorbing panel depends considerably on the arrangement of the absorbers in the room: in general, the absorption coefficient rises as the spacing between the panels is increased. There is some evidence to suggest, in addition, that for a given absorber size and spacing, the absorption coefficient of an individual absorber increases with the volume of the treated room. In the case of rectangular absorbers, the present results suggest that no difference in absorption occurs when the absorbers are arranged with either their long or their short dimension normal to the room surface, although other work suggests that a slight increase in absorption (at least at higher frequencies) is obtained with the long dimension normal to this surface.

There is no evidence to suggest that functional absorbers can be arranged to give absorption predominantly at low or mid-frequencies: the results of individual tests certainly show "peaks" and "troughs" of absorption at these frequencies, but none of these peaks are higher (or even approach) the absorption which occurs at high frequencies. Furthermore, these peaks are not well controlled, but depend markedly and in a not easily predicted manner on individual absorber arrangements.

6. ACKNOWLEDGMENT

The author is greatly indebted to P.H.C. Legate, who carried out all the practical work described in this Report.

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